A Covariance Study for Orbit Accuracy Improvement of the GPS Satellites Using Fiber Optics Tracking

N00014-90-J-2010

William S. Schreiner

Colorado Center for Astrodynamics Research
University of Colorado at Boulder
Boulder, Co 80309-0431

1991

BIOGRAPHY

William Schreiner received a B. S. degree in Aeronautical and Astronautical Engineering from Ohio State University in May 1988. He received a M. S. degree in Aerospace Engineering Sciences from the University of Colorado in May 1990. He is currently a third year Ph.D. student at the University of Colorado. William is a research assistant for the Colorado Center for Astrodynamics Research, and is specializing in the field of orbit determination.

ABSTRACT

With the use of the NAVSTAR Global Positioning System (GPS) constellation, it is possible for military and civilian users operating GPS receivers to compute accurate receiver positions in both low Earth orbit and on the surface of the Earth. This positioning accuracy is greatly dependent on the accuracy of the GPS orbits that are used in the estimation process. Unfortunately, current GPS orbit accuracy limits the amount of scientific information that can be retrieved from many geodetic applications such as oceanography and crustal dynamics where precise positioning is required. For example, the altimetric satellite TOPEX which carries a GPS receiver will need 50 to 100 centimeter accurate GPS orbits to answer many climate and global change issues such as mean sea level rise. This limitation of the current GPS orbit accuracy (i.e. 10 to 20 meters rms for USAF broadcast orbits) motivated the preliminary development of a new orbit determination system that could provide sufficient GPS orbit accuracy for the scientific community. This paper presents an alternative GPS orbit determination system that consists of a relatively closely spaced fiducial tracking network that is time and frequency synchronized by a fiber optic link. The paper describes the proposed fiber optics tracking system and presents preliminary results of a covariance study that indicate the possibility of achieving sub-meter orbit accuracy. The covariance analysis was completed with the Orbit Analysis Simulation Software (OASIS) which was developed at the Jet Propulsion Laboratory (JPL).

INTRODUCTION

With the use of the NAVSTAR Global Positioning System (GPS) constellation, it is possible to compute accurate receiver positions in both low earth orbit and on the surface of the earth. This positioning accuracy is directly proportional to the accuracy of the GPS orbits that are used in the estimation process. For very precise GPS positioning applications such as mean sea level and tectonic plate motion determination, the current GPS positioning accuracy is inadequate. The orbit for the oceanographic satellite TOPEX, which carries a GPS receiver, will need to be known to approximately 10 centimeters rms in the radial direction. By applying the rule of thumb for relative positioning [1] ($|db|/b = |dr|/r$), the GPS orbits will need to be known to the sub-meter level. In addition, regional crustal dynamic applications typically need about 1 part in 10^8 accuracy for over 1000 km baselines to adequately define geodetic motions [2].

The orbit determination system presently employed by the United States Air Force (USAF) GPS Control Segment relies on a world wide acquisition of tracking data to estimate accurate GPS orbits. However, atmospheric delay effects and the necessity to simultaneously estimate the orbit and clock parameters limits the orbit accuracy. At present, the broadcast orbits computed by the USAF that are downlinked in the broadcast message are accurate to 10-20 meters rms (along track, cross track and radial) within the time of applicability. Post computed precise orbits, which are presently accurate to ~5 meters rms (along track, cross track and radial) in a best case, are available from the U.S. National Geodetic Survey, the U.S. Naval Surface Weapons Center, the U.S. Geological Survey through the University of Texas, and the JPL. However, these orbits are provided anywhere from weeks to months after a campaign. Not only is there a time delay for receiving these post-computed orbits, there also are inherently large operational costs for these systems which filter down to the user. These systems are also vulnerable to the DoD policy of Selective Availability/Anti Spoof (SA/AS) [3] which involves degrading the broadcast orbits and/or dithering the frequency standard on board the

satellite. Furthermore, as a problem might develop with these non-defense precision GPS tracking orbits, the problem will tend to persist for days to weeks because the data processing is substantially behind real time. SA/AS is engaged on the Block II GPS satellites and remains a factor yet to be completely understood as to its long term impact on precision orbit determination.

These limitations on the GPS orbit accuracy motivated the preliminary study of a unique orbit determination system that could provide sufficient GPS orbit accuracy for scientific applications. This paper presents the proposed GPS orbit determination system that consists of a closely spaced (40km to 60km) fiducial tracking network that is time and frequency synchronized by a fiber optics link. This idea was originated by Professor P. F. MacDoran at the University of Colorado. The University of Colorado presently uses fiber optic circuits for instructional television between its Boulder, Denver and Colorado Springs campuses with further plans to link all of the universities of the state of Colorado. The fiber optics presents an important opportunity to configure a precision differential tracking array between these campuses where the fiber enables the distribution of nearly perfect clock signals. The challenge is to devise a method of exploiting the advantages of highly stable timing and reduced transmission media effects to overcome the reduced sensitivity of relatively short baselines compared to long baselines which are usually exploited for precision orbit determination. This paper describes some details of the proposed fiber optics tracking system and also presents some preliminary results of a covariance study that was performed on the proposed system to estimate the achievable GPS orbit accuracy.

PROPOSED ORBIT DETERMINATION SYSTEM

The orbit determination system being presented in this paper would operate in the inverse of conventional GPS positioning. Instead of determining differential receiver positions from accurate GPS orbits and ranging information, the GPS orbits would be determined from accurate geodetic receiver positions and singly differenced range observations.

The success of such a system would require the determination of very accurate inter-receiver and geocentric positions and accurate singly differenced pseudorange and carrier phase data. The presence of a SLR (Satellite Laser Ranging) and VLBI (Very Long Baseline Interferometry) site at Platteville, Colorado would be used to reference the network to the geocenter of the Earth and provide an angular tie to the quasar directions. By using GPS receivers in a differential mode, the stations in the tracking network could be referenced to the VLBI network with an uncertainty of approximately 5 millimeters using current GPS receiver technology [4]. This 5 millimeter uncertainty is possible provided that precision orbits from the NGS or DMA were initially used to establish the network. In the absence of SA/AS, current code-correlating technology utilizing pseudorange and carrier phase data could achieve inter-station uncertainties at the millimeter level [2].

Accurate singly differenced range data could be obtained by the use of a fiber optics link between stations. The optical fiber could synchronize the data acquisition to near hydrogen-maser stability of 1×10^{-15} which would eliminate the need to model possible unstable receiver clock performance, thus leaving more data strength for the determination of the orbit parameters. In addition, since the tracking stations will be relatively close, differencing the data between stations would cancel the satellite clock error, and reduce most of the atmospheric delay and could create a differenced data type with a few millimeter accuracy. A concentrated network will also give long arcs of simultaneously visible data for the stations which would give strong arcs of differenced data. This is possible because GPS satellites are in relatively high orbits and are thus visible for up to 6.5 hours. A block diagram of the proposed system is shown in Figure 1.

The proposed system could benefit from many assets available to the University of Colorado (CU). There is the possibility of linking the fiber optics cable to the NIST (National Institute of Standards and Technology) Cesium frequency standards in Boulder which would give an absolute frequency reference. This would supply each reference oscillator in each GPS receiver with Cesium frequency accuracy (3×10^{-14}) and hydrogen maser like stability (1×10^{-15}) between stations. In addition, the connection to NIST would enable the absolute calibration of the satellite epoch and oscillator offsets. A fiber optic link between stations would also enhance the near real-time capability of such a system so that as problems develop, they can be readily identified and corrected. It has been shown that fiber optics technology has the ability to disseminate time and frequency to Hydrogen maser stability over baseline lengths of 22 kilometers in the Goldstone Deep Space Communications Complex [5].

Another advantage of Colorado is its mile high altitude which is approximately one scale height for tropospheric water vapor. The amount of troposphere the satellite signal must travel through in Colorado is one-third less than that at sea level which results in less wet tropospheric degradation of the signal. Because the stations will be relatively close together, they will essentially see similar tropospheric delays. There may, however, be problems with the tropospheric cancelation in the summer months when storm cells pass over one station and not the others. These cells pass within 20 minutes and are unlikely to create errors that correlate to the 12 hour period signatures of the GPS orbits. Water vapor radiometers could be needed if range differencing did not minimize the residual tropospheric delay, although, the acquisition of tracking data to elevation angles of 5° should provide the opportunity to estimate the differential effects between the stations.

The accurate ranging information required for the proposed system to operate can be obtained because the GPS satellites transmit two very stable L-band carriers modulated by a unique pseudo-random noise (PRN) code for each satellite. Presently, there are two technologies capable of computing ranging information between the GPS satellites and the GPS receivers: code-correlating technology and codeless technology [6]. The code-correlating receivers, which replicate the PRN-codes used in the space vehicles, compute pseudoranges and carrier phase data to generate accurate range data. Because the code-correlating receivers need to duplicate the PRN code, they are susceptible to the DoD's SA/AS policy. This is not the case for the codeless receivers, which use the chipping frequencies of the satellite PRN generators and the second harmonic of the suppressed carriers to create a pseudorange data type. At CU, the Colorado Center for Astrodynamics Research (CCAR) will have access to both code-correlating (TRIMBLE 4000-SDT and TI 4100) and codeless (ISTAC 2002 series) receivers which both generate the necessary ranging information.

There is no reason to restrict the proposed system to only NAVSTAR GPS orbit determination. Daly and Dale at the University of Leeds have made recent discoveries of the transmission characteristics and PRN-codes of the Soviet GLONASS satellites [7]. The knowledge now exists to produce both code-correlating and codeless hybrid NAVSTAR/GLONASS receivers which have the ability to process pseudorange and carrier phase data. This type of receiver would allow users of the NAVSTAR/GLONASS hybrid receiver to increase positioning accuracy because of the potential for more satellites and improved satellite geometry. This would enhance global positioning beyond that intended by the separate systems, especially when the NAVSTAR and GLONASS constellations are not scheduled to be completed until 1993 or perhaps later.

The set up of the operational system would involve: referencing stations to the SLR/VLBI network, verifying data transmission links and frequency stabilities, acquiring and processing code-correlating and/or codeless data, and then estimating the orbits of the GPS satellites. The proposed system could be relatively inexpensive to set up and operate, and it could provide very accurate GPS orbits that are less expensive than current services and meet the accuracy demands of precise geodetic applications at least over North America. Assuming success in the initial system, it is conceivable that fiber optic tracking networks would be established elsewhere(i.e. Australia, Africa, USSR).

SOFTWARE OVERVIEW

A covariance analysis was performed on the proposed GPS fiber optic tracking network to determine what sort of uncertainty could be expected in the estimation of GPS orbits. This covariance study was conducted using the Orbit Analysis Simulation Software (OASIS) package developed at JPL. OASIS was designed specifically for the analysis of orbit determination scenarios for earth orbiters, especially the GPS.

The software consists of several modules which are designed to address the various aspects of the covariance analysis problem. The modules are called PATH/VARY, REGRES, PMOD, OAFILTER, AND OUTPUT PROCESSOR. PATH/VARY takes the input orbits and force model to generate the orbit trajectories and integrates the variational equations to form the state transition matrices. Input for the REGRES module includes; observation arc times, station locations, data types, data time steps, and variables for which measurement partials will be computed. REGRES then defines observation sequences and computes measurements partial derivatives. After REGRES, the PMOD module can be used to difference the data and generate simulated residuals. Finally, if the uncertainties for the a priori state and consider parameters are defined, the computed (data noise) and considered uncertainties of the orbit can then be generated using the OAFILTER module which utilizes a U-D factorized formulation. After the filter module is run, the OUTPUT PROCESSOR module uses the previously calculated transition matrices to map the computed and considered uncertainties to specified times. For a complete description of the capabilities of the OASIS software, see the OASIS Mathematical Description Guide [8].

COVARIANCE MODEL FOR THE PROPOSED SYSTEM

The goal of the covariance analysis on the proposed system was to determine if the expected GPS orbit uncertainty would be small enough to satisfy precise geodetic requirements. The covariance model used in this analysis represents an optimistic scenario to test the theoretical accuracy limit of the proposed tracking system. The characteristics of the covariance model used in this analysis are described below.

The orbit used in the covariance study was chosen so that it would pass directly over the tracking network, thus creating a long (~6 hour) arc of data. The epoch and orbit parameters which were obtained from a USAF broadcast almanac are;

epoch time = 7/11/89 14h 3m 20s UTC,

$a = 26560.397$ km	$e = .0082$
$i = 54.5763°$	$w = 161.6000°$
$\Omega = 29.7801°$	$M = 169.8113°$

The a priori uncertainties assumed for this almanac quality orbit were 100 meters in position and 1 millimeter/second in velocity. Lunar and solar perturbations along with an 8x8 GEM-T2 gravity field [9] were included to generate the trajectory and compute the appropriate partial derivatives. Perturbations due to solar radiation pressure and satellite thermal emission were not included in the model. In addition, the effects of UT1 and polar motion uncertainty on the orbit uncertainty were not included in the model.

The station locations were chosen to be in Boulder, Denver, and Fort Collins because of the existing fiber optic cable linking these stations. These three stations are nearly orthogonal with station separations of 40 to 60 kilometers. The station covariance matrix used for the three station network has the x,y,z components of each station perfectly correlated with one another which simulates a rigid network. The uncertainties in the

A-1

covariance matrix simulate uncertainties with respect to the geocenter. Geocentric station uncertainties of both 10 and 4 centimeters were used in the analysis. This is an optimistic station covariance matrix because the differential GPS positioning of the network relative to the SLR/VLBI site would lead to station inter-site uncertainties.

To obtain the millimeter tracking precision required for the proposed system, both the pseudorange and the carrier phase data would have to be singly differenced between stations for both the L1 and L2 transmissions so that the ionospheric errors could be calibrated to millimeter accuracy. In the analysis, these two data types were acquired and differenced every 10 seconds for elevation angles greater than 10 degrees. The data noise uncertainty for the pseudorange was assumed to be 40 centimeters every 10 seconds, while the uncertainty for the carrier phase for two cases was assumed to be 1 and 5 millimeters for 10 seconds. The 5 millimeter data noise uncertainty was chosen because a larger data noise results when the uncorrelated noise of both the L1 and L2 are added to calibrate out the ionospheric delay. The effect of the wet tropospheric zenith delay was also studied by estimating the zenith delays at the stations with a priori uncertainties of 10 centimeters. Singly differenced data eliminates both the satellite clock and receiver oscillator errors. In addition, there are no cycle slips from receiver oscillator instabilities because the fiber provides very stable reference frequency and time.

For each scenario that was studied, both the computed and considered uncertainty of the radial, along track, and cross track components of the GPS orbit were computed. The computed uncertainty is limited by the data noise and a priori orbit uncertainties. The considered uncertainty is equal to the computed uncertainty plus any uncertainty due to the constant consider parameters in the force and measurement models. Therefore, the considered uncertainty is always larger than the computed uncertainty and represents a more realistic (and sometimes pessimistic) orbit uncertainty.

In these covariance analyses, the state vector contained the orbit parameters of the GPS satellite and also the wet tropospheric zenith delay parameters when they were estimated. Preliminary analyses showed that the effects of the uncertainties in the 8x8 gravity field coefficients and increasing the a priori orbit uncertainties did not contribute to the considered uncertainty of the GPS orbit. Therefore, only the uncertainties in the station locations and GM of the earth (4×10^{-3} km^3/s^2) were considered.

RESULTS

The first scenario studied for the proposed tracking system was a 1 day arc having 1 pass of data. The corresponding computed uncertainty is shown in Figure 2. One can see that the magnitudes of the radial and cross track components are about 10 centimeters, but the along track component diverges to ~1.6 meters at the end of the 24 hour arc. When the uncertainties of the correlated station locations (10 cm) and GM were considered, the uncertainty increased to ~3.0 meters in the along track component as shown in Figure 3. These results are encouraging since correlating the station location errors is close to a realistic case.

In an attempt to lower the uncertainty, a second day arc was included in the analysis. It was assumed that errors in the gravity field would not contribute to the orbit uncertainty over a two day arc. In addition, the geocentric station location uncertainties were decreased to 4 centimeters which is near the present capability of SLR/VLBI. The considered uncertainty reached a maximum of 11 centimeters for the two day arc as seen in Figure 4. And finally, this same scenario was studied while estimating the wet tropospheric zenith delay (10 centimeter a priori uncertainty) for each station and increasing the carrier phase data noise to 5 millimeters. Figure 5 shows that this considered uncertainty reached a maximum of 50 centimeters over the two day arc.
These results of this optimistic tracking system scenario are encouraging. They are almost two orders of magnitude better than the accuracy currently provided by precise post-computed orbits. However, the covariance model needs to be modified to compute more realistic tracking errors and orbit uncertainties.

FUTURE WORK

The uncertainties computed in this analysis are encouraging, but an optimistic covariance model was used to generate these results. Future work will refine the current model to better represent an operational version of the proposed tracking system. The first improvement to this study will be to include the effects of the inter-site uncertainties between the stations to obtain a more realistic station covariance matrix. By knowing the station covariance matrices of the fiducial sites and the tracking scenario that will be used to position the operational network to the geocenter, the OASIS software package will be used to compute a realistic station covariance matrix for the proposed network. The effect of solar radiation force mismodeling and gravity errors over longer arcs will also need to be included. The orbit studied in this analysis was chosen to fly directly over the tracking station network which is a best case scenario. Other orbit geometries will need to be analyzed in future studies. The baselines lengths will be increased up to ~400km by moving the station locations to other campuses such as Colorado Springs and (Mesa State) Grand Junction. A trade study will then be performed between baseline length and residual tropospheric delay error to determine the optimum station separation and geometry.

CONCLUSIONS

The possibility of exploiting relatively closely spaced tracking sites connected by fiber optics to provide accurate clocks offers an interesting possibility for significant improvements in GPS orbit determination. The preliminary results presented in this paper are encouraging, but are also optimistic since the full array of potential error sources remains to be included. Assuming future studies continue to show that the proposed fiber optic orbit determination method is capable of determining GPS orbits with uncertainties less than 1 meter, then a transition would be made to hardware demonstration hopefully leading to an operational system. If the proposed system could determine GPS orbit accuracy of a few parts in 10^8, then the accuracy of measured geodetic information could improve by an order of magnitude which would greatly benefit the TOPEX oceanographic mission and the coming studies of sea level and the broad mission of climate and global change.

ACKNOWLEDGEMENTS

The author would like to thank Professor P.F.MacDoran for originating the proposed orbit determination system and for making many difficult topics more understandable. Also thanked are Professor K. Larson, and graduate students S. Mitchell, C. Tu, T. Kelecy and S. Pogorelc for their assistance in operating the unfriendly OASIS software package. The author also acknowledges the support of B. Douglas and W. Carter of the National Geodetic Survey for the preliminary analysis of the Fiber Optics GPS Orbit Network. Robert Gabriel of US WEST is also thanked for details of fiber optics network operations. G. Bardsley of the CU Department of Interdisciplinary Telecommunications is thanked for his help with fiber optics administrative coordination.

REFERENCES

1. Wells, David, Guide to GPS Positioning, Canadian GPS Associates, May 1987.

2. Blewitt G. et al, "GPS Geodesy: A status Report", High Precision Navigation, 1989.

3. NAVSTAR Operations Support Office, April 11, 1989.

4. MacDoran, Peter F., "Satellite Emission Radio Interferometric Earth Surveying, SERIES - GPS Geodetic System," Bulletin Geodesique, 53, 1979.

5. Primas L., Lutes G. and Syndor R., "Fiber Optic Frequency Transfer Link", Proceedings of the 42nd Annual Frequency Symposium, 1988.

6. MacDoran, P. F. and Spitzmesser, D.J., "Methods and Apparatus for Deriving Pseudo Range from Earth-Orbiting Satellites", United States Patent Number 4,797,677, January 10, 1989.

7. Daly P. and Dale S., British Scientists Reveal Signal Format of Soviet Navsat, Aviation Week & Space Technology, April,13 1987.

8. "Orbit Analysis and Simulation Software (OASIS): Mathematical Description", The Jet Propulsion Laboratory, Pasadena, California, April 1, 1986.

9. Marsh, J. G., et al., The GEM-T2 Gravitational Model, submitted to JGR, 1989b.

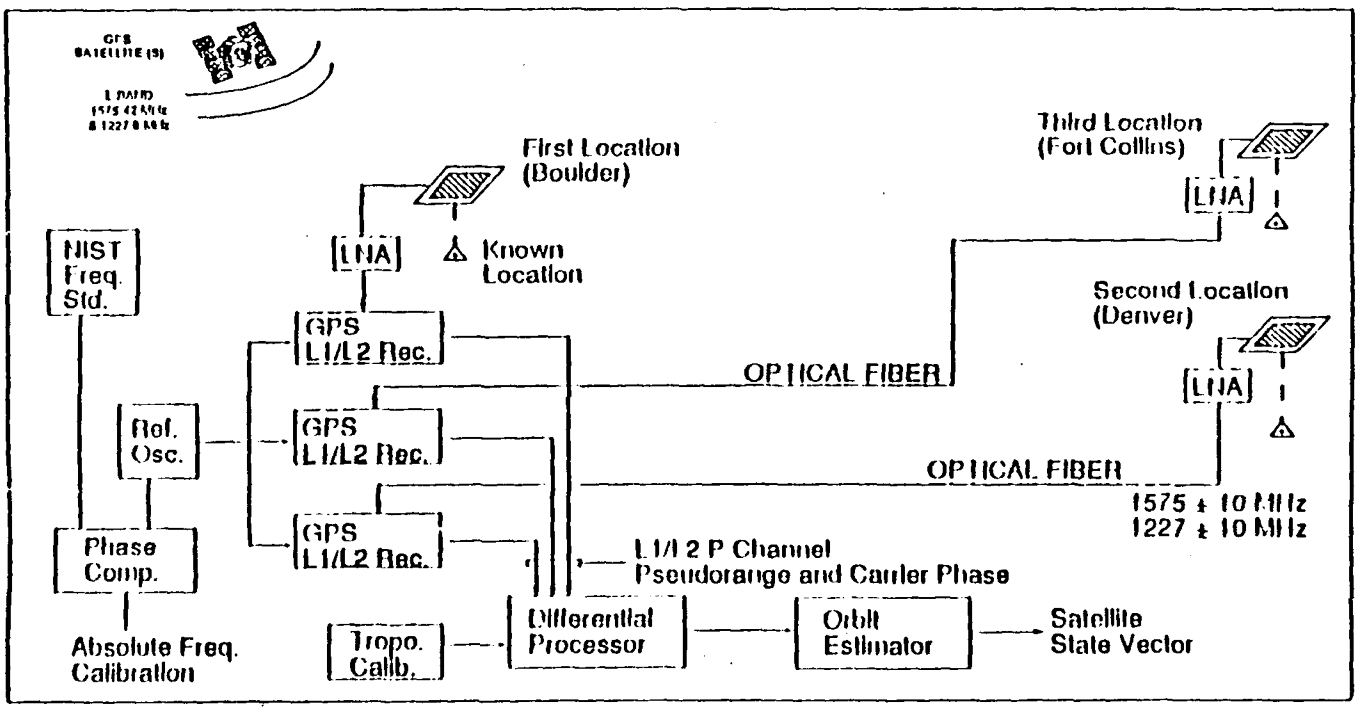

Figure 1. Block Diagram of the Proposed Fiber Optics Orbit Determination System

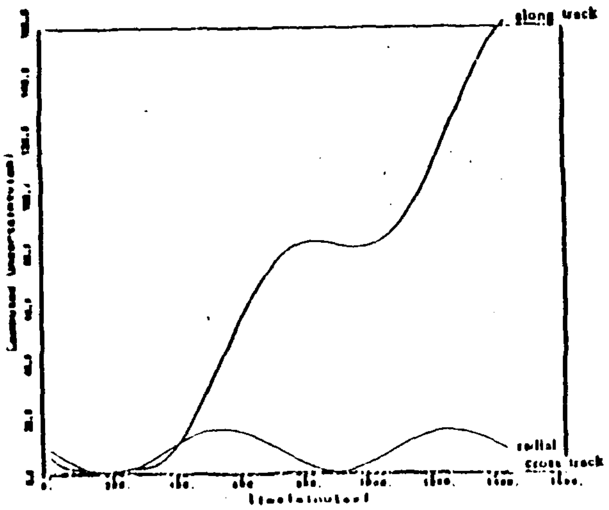

Figure 2. Computed Orbit Uncertainty for a 1 day arc.

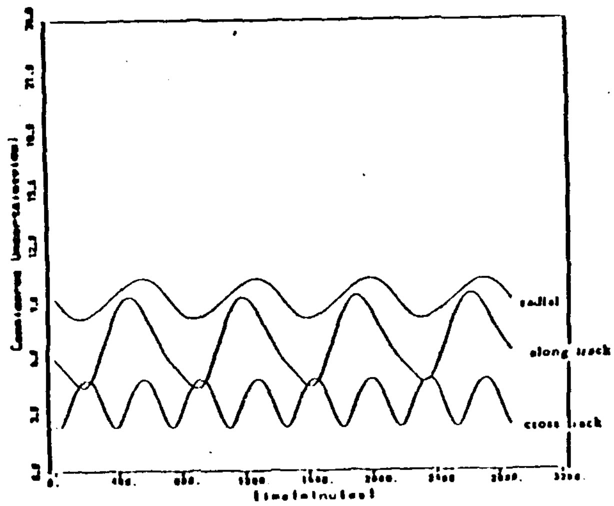

Figure 4. Considered Orbit Uncertainty for a 2 day arc. The errors in GM of the Earth and the station locations (4 cm) are considered.

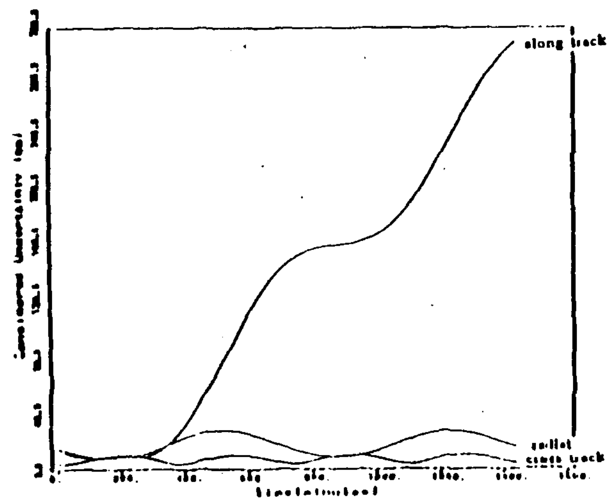

Figure 3. Considered Orbit Uncertainty for a 1 day arc. The errors in GM of the Earth and the station locations (10 cm) are considered.

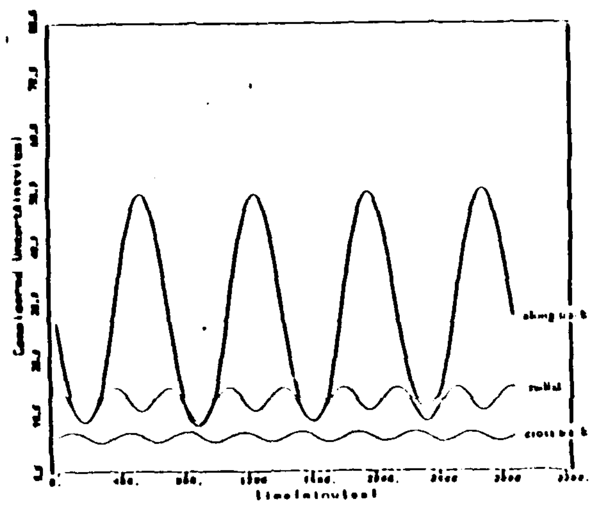

Figure 5. Considered Orbit Uncertainty for a 2 day arc. The errors in GM of the Earth and the station locations (4 cm) are considered. The tropospheric zenith delays for the 3 stations are estimated with a priori uncertainties of 10 cm. The carrier phase data noise is 5 mm.